Energy, Mines and Resources Canada | Énergie, Mines et Ressources Canada

**CANMET**

Canada Centre for Mineral and Energy Technology | Centre canadien de la technologie des minéraux et de l'énergie

# PRELIMINARY REPORT ON THE COMPARATIVE COMBUSTION PROPERTIES OF RAW AND WASHED PRINCE MINE COAL

G.N. Banks, J.K. Wong and H. Whaley

APRIL 1986

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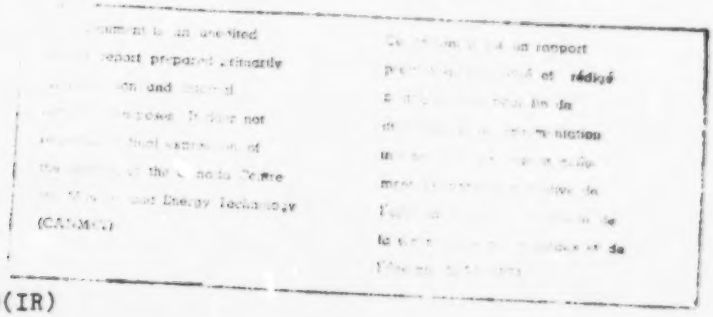

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# PRELIMINARY REPORT ON THE COMPARATIVE COMBUSTION PROPERTIES OF RAW AND WASHED PRINCE MINE COAL

by

G.N. Banks*, J.K. Wong** and H. Whaley***

## ABSTRACT

The combustion performance of raw Prince Mine coal (run of mine) and five levels of cleaned (washed) Prince Mine coal was compared with that of a commercially available thermal bituminous coal from Western Canada. Tests were conducted in a pilot-scale pulverized coal-fired research boiler located at the Energy Research Laboratories in Ottawa.

Two of the cleaned coal samples were obtained from the Electric Power Research Institute (EPRI), Homer City cleaning facility in the USA and the other three were obtained from CANMET's Coal Research Laboratories coal cleaning facility in Devon, Alberta. Chemical, physical, petrographic and thermogravimetric analyses were performed on samples of the coals. Each of the coals flowed readily through the Energy Research Laboratories pilot-scale conveying and coal-handling system.

The coals, which ground readily to produce a consistent size product from the pulverizer, all ignited easily to produce stable flames at greater than 96% combustion efficiency. The highest combustion efficiencies (>99%) were obtained with the more finely ground coal feeds. Although the two washed coals with the lowest ash content gave the higher combustion efficiencies, the raw coal, which had the lowest fly ash combustible content, also gave a combustion efficiency greater than 99%.

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The ash from each of the Prince Mine coals was quite fluid and slagged readily in the refractory-lined furnace bottom, whereas the ash deposits on the water-walls and superheater surfaces were light and powdery and did not constitute a fouling problem.

The sulphur content of the coal was not significantly lowered until the ash content of the coal was reduced to less than 7%. A reduction to 2.4% ash resulted in a 56% reduction in the sulphur content of the coal. This coal sample (containing 1.8% sulphur) burned in the utility boiler to produce a flue gas containing 0.9 g $SO_2$/MJ of fuel input compared to 3.0 g $SO_2$ for the raw coal, both of which are well above the Canadian $SO_2$ guideline of 0.258 g/MJ.

# RAPPORT PRÉLIMINAIRE SUR LES PROPRIÉTÉS DE COMBUSTION RELATIVES DU CHARBON BRUT ET DU CHARBON PROPRE PROVENANT DE LA MINE PRINCE

par

G.N. Banks*, J.K. Wong** et H. Whaley***

## RÉSUMÉ

Les propriétés de combustion du charbon brut de la mine Prince (charbon tout-venant) et de charbons propres à cinq diverses étapes de nettoyage ont été comparées à celles d'un charbon thermique bitumineux de l'Ouest canadien actuellement disponible sur le marché. Les essais ont été menés au moyen d'une chaudière expérimentale à l'échelle-pilote alimentée au charbon pulvérisé qui se trouve aux Laboratoires de recherche sur l'énergie à Ottawa.

Deux des échantillons de charbon propre provenaient du Electric Power Research Institute (EPRI), une laverie de Homer City aux États-Unis, et les trois autres provenaient de l'installation de lavage de charbon des Laboratoires de recherche sur le charbon du CANMET à Devon (Alberta). Les échantillons de charbon ont été soumis à des analyses chimique, physique, pétrographique et thermographique. Tous les charbons s'écoulaient bien dans le système de convoyage et de manutention expérimental des Laboratoires de recherche sur l'énergie.

Les charbons, qui étaient broyés sans difficulté, donnaient un produit d'une granulométrie régulière à partir du pulvérisateur, s'enflammaient facilement, produisaient des flammes stables et avaient un taux de combustion supérieur à 96 % . Le niveau de combustion le plus efficace (>99 %) a été obtenu avec des charges de charbon d'une granulométrie plus fine.

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Bien que les deux charbons propres qui contenaient le moins de cendre aient atteint les taux de combustion les plus élevés, le charbon brut, dont le contenu en cendre était moindre, a également eu un rendement de combustion supérieur à 99 % .

La cendre provenant de chacun des charbons de la mine Prince était très fluide et s'entartait facilement dans le fond de la chaudière qui était recouvert d'un produit réfractaire tandis que les dépôts de cendre sur les écrans d'eau et les surfaces du surchauffeur étaient légers et poudreux et ne constituaient pas un problème d'entartage.

La teneur en soufre du charbon n'a pas diminué de façon importante jusqu'à ce que la teneur en cendre ait été réduite à moins de 7 % Une réduction de la teneur en cendre à 2,4 % a causé une réduction de 56 % de la teneur en soufre du charbon. L'échantillon de charbon (titrant 1,8 % en soufre) a été brûlé dans une chaudière auxiliaire pour produire un gaz de carneau titrant 0,9 g $SO_2$/MJ en combustible additionnel comparativement à 3,0 g $SO_2$ pour le charbon brut: les deux échantillons de charbon avaient une teneur en $SO_2$ supérieure à celle stipulée dans les directives canadiennes qui est de 0,258 g/MJ.

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## INTRODUCTION

As part of an International Energy Agency (IEA) research program, CANMET has agreed to conduct pilot-scale combustion trials on a number of raw and cleaned coals. The IEA Coal Cleanability and Combustion Characterization Project was formed to investigate the effect of coal beneficiation on the combustion properties of the less amenable thermal coals. Due to the diminishing quality of thermal coals and the increasing world recognition of environmental responsibilities, interest in the effects of coal beneficiation on the combustion performance of cleaned coals has significantly increased.

The first coal in this series to be tested at CANMET was from the Cape Breton Development Corporation's (CBDC) Prince Mine, located on the Hub Seam in the Sydney coalfield. Cleaned coal test samples were produced from the Prince Mine raw coal by the Electric Power Research Institute (EPRI) Homer City coal cleaning facility in the USA and the CANMET Coal Research Laboratory (CLR) coal cleaning facility in Devon, Alberta. These coal samples were shipped to Ottawa, Ontario, where combustion performance evaluation tests were carried out by CANMET's Energy Research Laboratories (ERL) in a pilot-scale pulverized-coal-fired research utility boiler. The combustion results obtained on the cleaned and raw Prince Mine coals were compared with one another and with the test results obtained on a commercially available bituminous thermal coal sample (reference) from Western Canada.

This preliminary report describes the objectives of the project and gives the analyses of the coals. Based on these analyses, the coals' apparent quality, combustion reactivity, and potential ash slagging and fouling properties are assessed. The facilities and equipment utilized and the operational procedures selected to evaluate the coals' actual combustion performance are then described and the actual pilot-plant performance compared to the predicted values.

## RESEARCH OBJECTIVES

The objectives of this project included the following:

1. To quantify coal quality, chemistry and petrography.
2. To determine coal comminution and handling characteristics.

3. To evaluate the combustion performance of the pulverized coal at two fineness levels and at an excess air level corresponding to 4% oxygen in the flue gases.
4. To characterize the particulate and gaseous pollutants generated during combustion.
5. To assess the slagging and fouling potential of the coal ash constituents on radiant heat transfer surfaces and superheater tubes.
6. To assess the electrical resistivity characteristics of the fly ash and the ease of fly ash collection by electrostatic precipitation.
7. To generate coal combustion charts, based on heat losses calculated from the coal analyses.

## COAL CHARACTERISTICS

### HANDLING AND PREPARATION

Samples of coal were delivered to CCRL in sealed 45-gallon drums. The coals with their "as received" moisture, were free flowing and no problems were experienced in feeding them through the pilot-scale coal handling system.

### COMBUSTION REACTIVITY

The screen analyses and proximate, ultimate and ash analyses of the coal samples are listed in Tables 1 to 4. These analyses and the petrographic data given in Table 5 and Fig. 1 to 4 provide a guide for predicting "Combustion Reactivity". This term is generally understood as the ability of a coal to ignite readily and to produce a stable flame with acceptable carbon burn-out, without the necessity of support firing, when applied to the assessment of a potential thermal coal.

The volatile matter content of 31-42% suggests that these coals should ignite readily and the indicated percentage of reactive macerals in the coals (Table 5) is quite high (85-93%), which suggests that carbon burn-out of the coal should be excellent. Figure 1 illustrates the influence of different coal macerals on combustion reactivity and carbon burn-out. This figure indicates that the combustion efficiency of the Prince Mine coal (raw and washed) should be higher than that obtained with the reference thermal coal, due to the greater amount of exinite and reactive vitrinite macerals.

Another method used to predict the reactivity of the coal is to determine its burn profile in air by thermogravimetric analysis (Fig. 3 and 4). The reference coal reached its highest devolatilization rate of 7.8%/min at a reaction temperature of 400°C whereas the Prince Mine coal's highest devolatilization rate of 6.9%/min was not attained until a reaction temperature of 460°C was reached. This devolatilization rate (6.9%/min) was obtained with the washed coal containing 10.9% ash, compared with 5.9%/min at 456°C for the raw coal containing 24.5% ash. It was also noted that the Prince Mine samples exhibited an initial devolatilization peak occurring between 300 and 400°C, suggesting either the possibility of an earlier ignition at a lower rate of devolatilization or indications of an oxidized coal. This initial peak was quite predominant in the raw coal sample, but diminished as the ash content of the coal samples decreased. These thermogravimetric analyses indicate that the combustion efficiency of the reference thermal coal is superior to that of the raw Prince Mine coal as well as any of the Prince Mine washed products.

Hence, because of this apparent conflicting reactivity evidence, it is not possible to give a reasonable prediction of the behaviour of the Prince Mine coal samples without further corroborative support, such as pilot-scale combustion tests.

Combustion charts, based on the ultimate analyses of the raw Prince Mine coal sample, are given in Appendix A. These charts provide a rapid, graphical means of determining boiler efficiency by the indirect ASME heat loss method.

## HIGH TEMPERATURE ASH DEPOSITS

Two general types of high-temperature ash deposits can occur on the gas-side surfaces of coal-fired boilers:

1. Slagging - fused deposits that form on surfaces exposed predominantly to radiant heat transfer, such as on refractory furnace bottoms.
2. Fouling - high temperature bonded deposits that form on surfaces exposed predominantly to convective heat transfer, such as on superheater or reheater surfaces. Such deposits are not easily removed by soot-blowing procedures.

SLAGGING INDICATORS

The slagging potential of a coal can often be assessed by using indices or composite parameters to describe the nature and severity of the slag deposits (1). Two common indices for determining the slagging potential of the coal ash and furnace deposits are described below:

1. The base/acid ratio (B/A) is defined as:

$$B/A = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Al_2O_3 + TiO_2}$$

where each oxide is expressed as a percentage of the total ash. A maximum of 0.5 for the base/acid ratio has been suggested for dry-bottom pulverized-fired units, although this is not a necessary restriction. Values below 0.27 indicate that slagging is an unlikely problem at normal furnace operating temperatures.

2. Potential slagging temperature ($T_{ps}$) is defined as:

$$T_{ps} = \frac{HT + 4IT}{5} \ ^\circ C$$

where IT is the minimum temperature at which initial ash deformation occurs (normally in a reducing atmosphere) and HT is the maximum temperature at which hemispherical deformation occurs (normally in an oxidizing atmosphere). Temperature values greater than 1340°C indicate a low slagging potential, whereas values less than 1150°C indicate a severe slagging potential.

The base/acid ratio of 0.35 and the potential slagging temperature of 1194°C (Table 6), derived from the ash analysis and ash fusion data of the parent coal, suggest that the raw Prince Mine coal will have a high slagging tendency and should be burned in a wet bottom furnace. The comparative indices for the washed Prince Mine coals indicate an even higher and more severe slagging potential then was suggested for the raw Prince Mine coal.

FOULING INDICATORS

Most indices are applied by categorizing the coal as having an "eastern type" or "western type" ash. The term "western type" is defined as

an ash having more (CaO + MgO) than $Fe_2O_3$, on a per cent weight basis. On the above basis, the ashes from the Prince Mine coals ha[illegible] CaO + MgO:$Fe_2O_3$ ratios <0.20 thus can be classified as "eastern type" ashes. This criterion depends solely on ash analyses and does not have any rank or geographic connotation.

There has been general agreement between research and operating practice that one of the dominant factors influencing superheater fouling is the sodium content of the coal ash. The following classification has been proposed:

| Fouling category | % $Na_2O$ in ash | |
|---|---|---|
| | "eastern type" ash $\frac{CaO + MgO}{Fe_2O_3}$ <1.0 | "western type "ash $\frac{CaO + MgO}{Fe_2O_3}$ >1.0 |
| Low | <0.5 | <2.0 |
| Medium | 0.5 - 1.0 | 2.0 - 6.0 |
| High | 1.0 - 2.5 | 6.0 - 8.0 |
| Severe | >2.5 | >8.0 |

The Prince Mine coal ashes have a $Na_2O$ content ranging from 0.60 to 0.96% (Table 3), which indicates that they are in the medium fouling category of the "eastern type" ash.

Another possible indication of the fouling potential of a coal is based on its ash content, as outlined below:

| Fouling potential | Ash content, wt % |
|---|---|
| Low | <15 |
| Medium | 15 - 25 |
| High | >25 |

The raw Prince Mine coal has an ash content of 24.5% (Table 2), indicating that it is in the medium fouling category whereas all of the washed Prince Mine coals (<11% ash) would be considered to be in the low fouling category.

## PILOT-SCALE RESEARCH BOILER

The CCRL pilot-scale research boiler is a pulverized coal-fired boiler incorporating two opposing low-swirl burners (Fig. 5). The furnace is U-shaped and consists of a vertical refractory shaft and a vertical steam boiler, which are connected at the bottom through a horizontal refractory tunnel. This boiler can be fired by the twin low-swirl burners located in four basic positions: A, B, C or D, more commonly known as the I, J, $J_1$ and U configurations, respectively. It is expected that highly reactive fuels will burn efficiently when fired in the I configuration, but for fuels that are difficult to burn, residence times and combustion zone temperatures can be increased by locating the twin burners in the U configuration. Intermediate residence times, if required, can be obtained by locating the burners in the J or $J_1$ configurations. It is estimated that at full load and with the burners located in the I configuration, the combustion chamber residence time will be about one second. This residence time will increase to about three seconds with the burners located in the U configuration. The combustion chamber heat release rate is about 0.35 $MJ/s/m^3$.

The three sections of the furnace are designed to operate at pressures up to 2.5 kPa (250 mm of water). At the full-load firing rate of 2.5 GJ/h (0.7 MW), the boiler generates about 730 kg/h of steam at 690 kPa. It is possible to control the furnace exit temperature by adding cooled-wall panels in the refractory shaft or by partially insulating the water walls of the boiler.

Crushed coal is supplied to the furnace from a 4500 kg hopper, mounted on an electronic weigh scale, through a variable-speed worm feeder to a ring-and-roller type of pulverizer, which is normally swept and pressurized by air at temperatures up to 230°C. If necessary, the pulverizer can be swept and pressurized with a mixture of air and flue gas at temperatures up to 400°C. The pulverizer contains a motor-driven classifier for controlling coal fineness and a riffle at the pulverizer outlet proportions the coal to each burner. Secondary air can be supplied to the burner at temperatures up to 260°C.

Combustion gases leave the furnace between 900°C-1300°C, then pass through a transition section, a test-air heater and a conventional three-pass air heater before entering a long horizontal sampling duct. A bypass from

the air heater to the stack breeching and an additional heat exchanger surface in the sampling duct permit the gas temperature in the sampling duct to be varied from 150°C to 300°C.

A forced-draft fan supplies air to the air heater at 7 kPa (71 cm. WC). The air, on leaving the heater, is divided into three systems: primary air to the pulverizer, secondary air to the burners and cooling air to the test air heater. The last stream, after leaving the test-air heater, can either be exhausted to the atmosphere or blended with the primary air supply to the pulverizer.

The research boiler is manually controlled, except for electrical interlocks to ensure that safe startup and shutdown procedures are followed. When burning high-grade coals, it has been possible to operate with as little as 1.0% $O_2$ and less than 100 ppm CO in the flue gases, with a smoke density of less than No. 1 Ringlemann.

## EXPERIMENTAL PROCEDURES

### OPERATING PROCEDURE

The following procedure, with minor variations in timing, was used for all trials:

1. Before each test, all boiler and air heater fireside surfaces were thoroughly cleaned by air lancing and the furnace bottom was lined with a refractory blanket. Sufficient coal was bunkered to provide 7 h continuous operation.
2. At 0800 h, the cold boiler was preheated with No. 2 fuel oil fired at 10 g/h, using two oil torches. Excess air was adjusted to provide 5% $O_2$ in the flue gas and the boiler was allowed to stabilize at full steaming rate and pressure. All continuous monitoring instruments were activated.
3. At 0920 h, pulverized coal was fed to the boiler at a specified classifier speed, mill temperature and excess air level. One oil torch was left in operation.
4. After flame stability was established, the oil torch was removed, allowing the boiler to operate on pulverized coal only.

5. At 1100 h, scheduled testing was begun. Boiler panel readings were monitored continuously and recorded every half hour. A specified coal feed rate, coal fineness and excess air level were maintained as closely as possible for the test duration.
6. By 1600 h, all measurements were completed and the boiler was shut down.
7. The furnace was allowed to cool overnight. The furnace bottom was then removed, the duct works were dismantled and the ash in the furnace bottom and duct work were photographed, collected, weighed and sampled.

PARAMETERS OF COMBUSTION PERFORMANCE

The following combustion performance parameters were measured at the sampling stations illustrated in Fig. 4:

1. Coal quality of a composite sample was taken from the crushed coal feed at the pulverizer inlet. Station 1.
2. Moisture and sieve analyses of pulverized coal samples were taken at the pulverizer outlet. Station 2.
3. $O_2$ content of the flue gas was measured continuously by a Dynatron oxygen analyzer and a paramagnetic monitor. Stations 8 and 10, respectively.
4. $NO_x$ content of the flue gas was measured continuously by a chemiluminescent monitor. Station 10.
5. CO and $CO_2$ contents of the flue gas were measured continuously by infrared monitor. Station 10.
6. $SO_2$ and $SO_3$ contents of the flue gas were measured continuously by ultra-violet and absorption colorimetric methods. Stations 10 and 13, respectively.
7. Low-temperature corrosion potential was measured by three mild steel probes which were inserted simultaneously into the flue gas stream and maintained at three different temperatures for the duration of the combustion test. Station 9.
8. Fly-ash loading was measured by an isokinetic sampling system, three samples per test. These samples were analyzed for carbon content and dust loading. Stations 15 and 16.

9. Aerodynamic size distribution was determined in a fractionating sampler and in a Cascade cyclone sampler. Station 12.
10. Fouling of heat-transfer surfaces was evaluated by visual examination and chemical composition of ash build-up on a simulated superheater, installed immediately downstream of the screen tubes. Station 7.
11. Slagging propensity was determined by examining the thickness, physical structure, chemical composition and melting characteristics of ash deposits selected from various parts of the furnace. Stations 3 to 6.
12. Fly-ash resistivities were measured by an in situ, point-plane resistivity apparatus at flue gas temperatures of approximately 300°C at Station 11, and 180°C at Station 14.

## COMBUSTION PERFORMANCE

### COAL COMMINUTION

The Prince Mine coals crushed, dried, metered and pulverized to the selected degree of fineness without difficulty. The CCRL coal drying and grinding system is illustrated in Fig. 6. The pulverized coals were then transported directly to the burners without moisture separation from the carrying air. The size distribution of the pulverized coals for each of the trials is shown in Tables 7 and 8. A coarse grind (70 to 80% - 200 mesh) was maintained for the trials (C-1A to C-7A) in Table 7, while a finer grind (>80% - 200 mesh) was maintained for the trials (C-1B to C-7B) in Table 8.

### BOILER OPERATION AND FLAME CHARACTERISTICS

The combustion conditions remained essentially constant between 2000 and 2300 MJ/h input for all furnace trials. The flame was bright, clean and stable under reasonably steady-state conditions and an oil support flame was required for only a few minutes at the start of each trial. It should be noted that the coals were fired in the I furnace configuration for all of the furnace trials.

## GASEOUS EMISSIONS

The average flue gas analyses for each combustion trial are summarized in Tables 7 and 8. The carbon monoxide levels, at less than 100 ppm, do not constitute either an emission problem or a significant thermal penalty.

The sulphur dioxide emissions from this coal were 0.91 to 3.09 g $SO_2$/MJ, which is much higher than the current Canadian national emission guideline of 0.258 g $SO_2$/MJ of fuel input for new combustion systems (2). The nitric oxide emission rates of 0.38 to 0.42 g $NO_x$/MJ are well above the current Canadian national emission guideline of 0.168 g $NO_x$/MJ of fuel input, but this level is specific to the CCRL equipment and it can be significantly improved through the use of modern low-$NO_x$ burner technology.

## FLY ASH CHARACTERISTICS AND COAL BURN-OUT

The mass loadings, aerodynamic particle size and combustible content of the fly ash for each trial are summarized in Tables 9 and 10. These data indicate, as expected, that the fly ash loadings are higher for the coals containing a greater percentage of ash. It is also clearly evident that the more finely ground coal results in a lower combustible content in the fly ash. This lower combustible content obviously effects the calculated combustion efficiency of the higher ash coals more acutely than those containing little ash.

In general, high electrical resistivity (>10 log ohm-cm) indicates that precipitated fly ash will retain a strong electrical charge and repel any similarly charged particles or generate a back corona within the deposit; precipitation, conversely, is therefore difficult. A low resistivity (<7 log ohm-cm) fly ash will readily precipitate but will not adhere strongly to the collecting plates and will easily be re-entrained in the flue gas. Intermediate resistivity values of approximately 8 to 9 log ohm-cm are considered to yield the best precipitator efficiencies.

The measured in situ electrical resistivity of the fly ash from each of the trials, with one exception, was approximately 5 log ohm-cm. This one exception was the finely ground raw coal, (trial 2B), which had an electrical resistivity >7.0 log-ohm cm. It is suspected that this was due to the much lower combustible content of the fly ash.

ASH SLAGGING AND FOULING

The calculated potential slagging temperature and the base/acid ratio shown in Table 6 indicate a high-to-severe slagging propensity for the Prince Mine coal samples compared with the medium propensity of the reference coal. This severe slagging of the Prince Mine coal samples was confirmed by the combustion trials. The analytical data on the parent coal ashes also predicted a low to medium-fouling tendency which was confirmed by powdery, loosely adherent deposits formed on the water-walls and convective heat tranfer surfaces.

## CONCLUSIONS

The Prince Mine coals handled and flowed without difficulty, resulting in a ground coal product which ignited readily to produce stable combustion flames, quite similar in appearance to one another and to the reference thermal coal.

The petrographic data and coal analyses suggested that the carbon burn-out from the Prince Mine coals (raw and washed) should be excellent, but thermogravimetric analyses indicated that the combustion reactivity of these coals will be lower than that of the reference coal. Combustion studies in the utility boiler indicated that the raw Prince Mine can be burned to less than 6% combustible in the fly ash with a coarse grind (72% - 200 mesh) and less than 2 1/2% combustible content with a fine grind (97% - 200 mesh), while the washed coals burned to combustible contents of 9 to 24% in the fly ash, varying with the grind and ash content of the coal. These figures compare to a 2.9% combustible content in the fly ash from the thermal reference coal, containing 10.7% ash and fired at a grind of 90% - 200 mesh, to give a 99.9% combustion efficiency (higher than any of the Prince Mine coal samples).

Washing the Prince Mine coal reduced the sulphur content of the coal by 6% to 56% (depending on the amount of ash removed). The overall reduction in $SO_2$ evolved in the flue gas (g/MJ of fuel input) compared with the raw coal varied from 34% to 70%, with the highest $SO_2$ reduction as a result of the highest ash removal. Moreover, the lowest emission rate of 0.906 g $SO_2$/MJ is still well above the current Canadian emission guideline of 0.258 g $SO_2$/MJ of fuel input as well as the 0.228 g $SO_2$/MJ of fuel input obtained with the thermal reference coal.

The tendency of the coal ash to slag was predicted to be high to severe from the analytical data on the parent Prince Mine raw and washed coal samples. This prediction was confirmed by the fluid slag produced in the refractory-lined furnace bottom. The analytical data also indicated a low to medium-fouling tendency, which was consistent with the powdery, easily removed ash material deposited on the water-walls and the superheater tubes during the combustion trials.

## ACKNOWLEDGEMENTS

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2. Thermal Power Generation Emissions - National Guidelines for New Stationary Sources, Canada Gazette; April 25, 1981.

Table 1 - Screen analysis of Prince Mine coal samples

| Screen size (mm) | Weight % (cumulative) | | | | | |
|---|---|---|---|---|---|---|
| | Raw coal C-2 | Devon washed C-3 | Devon washed C-4 | EPRI washed C-5 | Devon washed C-6 | EPRI washed C-7 |
| +25.4 | 9.71 | - | - | - | - | 0.26 |
| +19.1 | 15.12 | - | - | 0.18 | - | 0.96 |
| +12.7 | 25.98 | 0.99 | 0.31 | 2.84 | 0.49 | 7.36 |
| +6.4 | 48.64 | 12.57 | 8.00 | 19.23 | 10.13 | 28.64 |
| +3.2 | 70.14 | 53.51 | 42.05 | 56.22 | 50.43 | 59.82 |
| -3.2 | 9.86 | 46.49 | 57.95 | 43.78 | 49.57 | 40.18 |
| Bulk density ($kg/m^3$) | 851 | 692 | 649 | 705 | 672 | 689 |
| % moisture | 9.2 | 6.3 | 7.1 | 6.7 | 6.4 | 7.1 |

Table 2 - Coal analyses

| Component | Ref. coal | Prince Mine (P.M.) coals | | | | | | Pacific rim specifications | |
|---|---|---|---|---|---|---|---|---|---|
| | | Raw | Devon Washed | | EPRI washed | Devon washed | EPRI washed | | |
| | C-1 | C-2 | C-3 | C-4 | C-5 | C-6 | C-7 | KECO | EPDE |
| Moisture, wt % | | | | | | | | | |
| As received | 5.25 | 1.56 | 7.55 | 7.68 | 1.54 | 6.46 | 2.00 | < 15 | < 10 |
| Equilibrium | 10.48 | 6.34 | 6.17 | 5.96 | 5.69 | 5.77 | 6.16 | - | - |
| Proximate, wt (dry) | | | | | | | | | |
| Ash | 10.72 | 24.54 | 10.88 | 7.64 | 6.97 | 5.21 | 2.41 | < 17 | < 20 |
| Volatile matter | 33.88 | 31.14 | 39.32 | 42.43 | 37.90 | 32.17 | 37.27 | 22-36 | $\frac{V.M.}{F.C.} > 0.4$ |
| Fixed carbon | 55.40 | 44.32 | 49.80 | 49.93 | 55.13 | 62.62 | 60.32 | 50-60 | |
| Ultimate, wt % (dry) | | | | | | | | | |
| Carbon | 69.50 | 58.64 | 71.57 | 75.09 | 74.79 | 77.72 | 80.20 | - | - |
| Hydrogen | 4.26 | 4.10 | 4.93 | 5.00 | 5.04 | 5.29 | 5.39 | - | - |
| Sulphur | 0.33 | 4.21 | 3.96 | 3.28 | 3.92 | 2.89 | 1.84 | < 1.0 | < 1.0 |
| Nitrogen | 1.14 | 1.34 | 1.53 | 1.72 | 1.70 | 1.65 | 1.81 | <2.0 | <1.8 |
| Ash | 10.72 | 24.54 | 10.88 | 7.64 | 6.97 | 5.21 | 2.41 | - | - |
| Oxygen (by diff) | 14.05 | 7.17 | 7.13 | 7.27 | 7.58 | 7.24 | 8.35 | - | - |
| Calorific value, MJ/kg | 27.15 | 24.21 | 29.56 | 30.95 | 31.52 | 32.09 | 33.46 | >25.12 | >25.12 |
| Hardgrove grindability index | 38 | 69 | 58 | 56 | 61 | 57 | 58 | >45 | >45 |
| Chlorine in coal, wt % | <0.01 | 0.30 | 0.35 | 0.39 | 0.30 | 0.47 | 0.43 | - | - |
| Free swelling index | N.A.* | 2.5 | 5.5 | 6.0 | 5.0 | 5.0 | 3.5 | - | - |
| Ash Fusibility, °C | | | | | | | | | |
| Reducing atmosphere | | | | | | | | | |
| Initial deformation | 1196 | 1138 | 1071 | 1082 | 1091 | 1102 | 1088 | >1250 | - |
| Spherical softening | 1256 | 1374 | 1099 | 1127 | 1113 | 1121 | 1138 | - | - |
| Hemispherical deformation. | 1416 | 1391 | 1246 | 1293 | 1249 | 1154 | 1318 | - | - |
| Fluid temperature | >1482 | 1421 | 1332 | 1360 | 1382 | 1271 | 1441 | - | - |
| Oxidizing atmosphere | | | | | | | | | |
| Initial deformation | 1260 | 1352 | 1385 | 1382 | 1371 | 1388 | 1316 | - | - |
| Spherical softening | 1324 | 1404 | 1418 | 1413 | 1416 | 1435 | 1379 | - | >1200 |
| Hemispherical deformation. | 1402 | 1421 | 1421 | 1421 | 1421 | 1440 | 1393 | - | - |
| Fluid temperature | >1482 | 1443 | 1424 | 1421 | 1432 | 1449 | 1421 | - | >1300 |

*Non-agglomerating

Table 3 - Analyses of parent coal ash

| Major elemental oxides (wt %) | Ref. coal | P.M. raw | Devon washed | | EPRI washed | Devon washed | EPRI washed |
|---|---|---|---|---|---|---|---|
| | C-1 | C-2 | C-3 | C-4 | C-5 | C-6 | C-7 |
| $SiO_2$ | 58.72 | 47.92 | 37.31 | 33.71 | 27.04 | 22.40 | 30.80 |
| $Al_2O_3$ | 17.46 | 23.50 | 21.61 | 19.45 | 15.59 | 15.17 | 21.80 |
| $Fe_2O_3$ | 5.93 | 19.76 | 33.42 | 36.16 | 49.80 | 53.99 | 32.76 |
| $TiO_2$ | 0.84 | 0.82 | 0.82 | 0.84 | 0.72 | 0.70 | 0.99 |
| $P_2O_5$ | 0.21 | 0.07 | 0.03 | 0.05 | 0.05 | 0.00 | 0.03 |
| CaO | 7.47 | 1.30 | 1.10 | 1.78 | 1.14 | 1.67 | 3.76 |
| MgO | 1.15 | 1.02 | 0.76 | 0.76 | 0.47 | 0.69 | 1.08 |
| $SO_3$ | 3.54 | 1.63 | 0.70 | 1.98 | 1.28 | 1.05 | 3.26 |
| $Na_2O$ | 0.43 | 0.61 | 0.62 | 0.75 | 0.70 | 0.96 | 0.94 |
| $K_2O$ | 0.77 | 2.48 | 1.81 | 1.60 | 1.07 | 0.93 | 1.41 |
| BaO | 0.64 | - | 0.16 | 0.22 | - | 0.15 | - |
| SrO | 0.06 | - | 0.01 | 0.01 | - | - | 0.03 |
| L.O.F. | 0.82 | 0.77 | 0.53 | 0.88 | 0.78 | 0.59 | 0.73 |

Table 4 - Trace elements determined in coal samples (ppm)

| | Neutron activation analyses, ppm (dry basis) | | | | | | |
|---|---|---|---|---|---|---|---|
| | C-1 | C-2 | C-3 | C-4 | C-5 | C-6 | C-7 |
| Antimony (Sb) ..... | 0.7 | 1.7 | 1.0 | 0.8 | 1.0 | 0.7 | 0.3 |
| Arsenic (As) ..... | 3.4 | 106 | 64.9 | 48.1 | 63.1 | 38.1 | 18.7 |
| Barium (Ba) ..... | 436 | 86 | 39 | 20 | 36 | <15 | <14 |
| Bromine (Br) ..... | 1.1 | 52.8 | 61.3 | 62.4 | 67.9 | 68.4 | 73.5 |
| Caesium (Cs) ..... | 0.5 | 3.0 | 1.4 | 0.8 | 0.4 | <0.3 | <0.2 |
| Cerium (Ce) ..... | 12.1 | 30.0 | 15.0 | 10.8 | 9.1 | 7.7 | 4.9 |
| Chlorine (Cl) ..... | 33.0 | 2770 | 3060 | 3280 | 3490 | 3440 | 3900 |
| Chromium (Cr) ..... | 7.3 | 30.6 | 15.0 | 10.0 | 10.6 | 11.0 | 6.6 |
| Cobalt (Co) ..... | 2.1 | 6.9 | 4.0 | 3.0 | 3.7 | 2.2 | 1.1 |
| Copper (Cu) ..... | 8.3 | 36.2 | 13.4 | 14.3 | 19.3 | 12.2 | 10.2 |
| Dysprosium (Dy) .... | 1.3 | 1.6 | 1.1 | 1.0 | 1.0 | 0.8 | 0.7 |
| Europium (Eu) ..... | 0.2 | 0.4 | 0.3 | 0.2 | 0.2 | 0.2 | 0.1 |
| Hafnium (Hf) ..... | 1.0 | 0.9 | 0.6 | 0.4 | 0.3 | <0.2 | <0.1 |
| Holmium (Ho) ..... | 3.0 | 0.5 | <0.5 | <0.5 | 0.2 | <0.5 | <0.1 |
| Iodine (I) ..... | <0.5 | <0.4 | 1.6 | 1.9 | 0.3 | 1.5 | 0.4 |
| Lanthanum (La) ..... | 6.1 | 15.3 | 7.7 | 5.3 | 4.6 | 3.4 | 2.5 |
| Lutecium (Lu) ..... | <0.1 | 0.1 | <0.1 | <0.1 | <0.1 | <0.1 | <0.1 |
| Manganese (Mn) ..... | 69.8 | 91.0 | 34.8 | 33.0 | 27.2 | 30.5 | 14.7 |
| Molybdenum (Mo) .... | 2.1 | 7.4 | 5.7 | 4.8 | 5.3 | 4.3 | 2.6 |
| Neodymium (Nd) ..... | 5.6 | 9.1 | 7.0 | 6.4 | 3.5 | <2.8 | 3.2 |
| Nickel (Ni) ..... | <31 | <40 | <47 | <43 | <30 | <38 | <17 |
| Rubidium (Rb) ..... | 7.7 | 33.0 | 12.0 | <190 | 5.7 | <6.4 | <2.8 |
| Samarium (Sn) ..... | 1.1 | 2.1 | 1.3 | 1.0 | 0.9 | 0.8 | 0.5 |
| Scandium (Sc) ..... | 1.7 | 4.9 | 2.5 | 2.0 | 1.7 | 1.4 | 0.8 |
| Strontium (Sr) ..... | 86.0 | 130 | 54.0 | <32.0 | 48.0 | <30 | <29 |
| Tantalum (Ta) ..... | <0.2 | 0.3 | 0.1 | <0.1 | 0.1 | <0.1 | <0.1 |
| Terbium (Tb) ..... | <0.2 | <0.2 | <0.6 | <0.2 | <0.1 | <0.2 | 0.1 |
| Thorium (Th) ..... | 2.4 | 3.9 | 1.9 | 1.5 | 1.0 | 1.0 | 0.6 |
| Uranium (U) ..... | 1.2 | 1.0 | 0.6 | 0.5 | 0.4 | 0.4 | 0.2 |
| Vanadium (V) ..... | 12.5 | 46.2 | 27.0 | 23.0 | 24.3 | 18.1 | 10.7 |
| Ytterbium (Yb) ..... | 0.7 | 1.0 | 0.6 | 0.3 | 0.5 | 0.3 | 0.2 |
| Zinc (Zn) ..... | <10 | 37.0 | 29.0 | 54.0 | 16.0 | 23.0 | 14.0 |

Table 5 - Petrographic examination of coal macerals

| Maceral form | C-1 | C-2 | C-3 | C-4 | C-5 | C-6 | C-7 |
|---|---|---|---|---|---|---|---|
| Reactives | | | | | | | |
| Exinite ..... | 4.6 | 6.0 | 6.8 | 4.8 | 5.0 | 5.8 | 5.1 |
| Vitrinite ..... | 67.4 | 77.7 | 75.9 | 79.9 | 81.4 | 82.1 | 86.2 |
| Reactive semi-fusinite ... | 4.5 | 1.0 | 2.0 | 1.7 | 1.7 | 1.3 | 1.2 |
| Sub-total ..... | 76.5 | 84.7 | 84.7 | 86.4 | 88.4 | 89.2 | 92.5 |
| Inerts | | | | | | | |
| Fusinite ..... | 9.8 | 2.3 | 2.3 | 3.2 | 3.0 | 3.0 | 1.8 |
| Semi-fusinite ..... | 9.0 | 2.1 | 3.9 | 3.5 | 3.4 | 2.5 | 2.5 |
| Micrinite ..... | 2.0 | 0.9 | 2.0 | 1.9 | 0.8 | 1.8 | 1.4 |
| Mineral matter ..... | 2.7 | 10.0 | 7.1 | 5.0 | 4.7 | 3.5 | 1.8 |
| Sub-total ..... | 23.5 | 15.3 | 15.3 | 13.6 | 11.9 | 10.8 | 7.5 |
| Mean reflectance, % | 0.58 | 0.70 | 0.73 | 0.76 | 0.71 | 0.74 | 0.70 |

Table 6 - Comparative indices of slagging potential of parent coals

| Slagging propensity | Reference limits | Parent coal ash | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | C-1 | C-2 | C-3 | C-4 | C-5 | C-6 | C-7 |
| Base/Acid (B/A) Ratio | | | | | | | | |
| Low ..... | <0.15 | - | - | - | - | - | - | - |
| Medium ..... | 0.15 - 0.30 | 0.20 | - | - | - | - | - | - |
| High ..... | 0.27 - 0.50 | - | 0.35 | - | - | - | - | - |
| Severe ..... | <0.50 | - | - | 0.63 | 0.76 | 1.23 | 1.52 | 0.75 |
| Potential Slagging Temp, (Tps, °C) | | | | | | | | |
| Low ..... | <1340 | - | - | - | - | - | - | - |
| Medium ..... | 1340 - 1230 | 1240 | - | - | - | - | - | - |
| High ..... | 1230 - 1150 | - | 1194 | - | 1150 | 1157 | 1170 | - |
| Severe ..... | <1150 | - | - | 1141 | - | - | - | 1149 |

Table 7 - Boiler operating conditions (coarse grind)

| Components | C-1A | C-2A | C-3A | C-4A | C-5A | C-6A | C-7A |
|---|---|---|---|---|---|---|---|
| Furnace configuration | I | I | I | I | I | I | I |
| Fuel rate, kg/h | - | 85.7 | 69.8 | 67.9 | 67.1 | 67.6 | 69.5 |
| Fuel moisture, wt % | - | 0.23 | 0.64 | 0.72 | 0.00 | 0.00 | 0.00 |
| Coal fineness, wt % (Cdn std) | | | | | | | |
| +100 mesh | - | 0.6 | 0.6 | 0.4 | 0.7 | 0.7 | 0.5 |
| -100 + 140 mesh | - | 3.1 | 9.6 | 4.8 | 2.1 | 7.6 | 2.7 |
| -100 + 200 mesh | - | 23.3 | 17.5 | 17.5 | 17.1 | 19.5 | 24.5 |
| -200 + 325 mesh | - | 56.8 | 41.5 | 45.6 | 63.5 | 52.7 | 59.2 |
| -325 + 400 mesh | - | 9.2 | 16.1 | 17.7 | 7.9 | 10.4 | 5.8 |
| -400 mesh | - | 7.0 | 14.7 | 14.0 | 8.8 | 9.1 | 7.3 |
| -200 mesh | - | 73.0 | 72.3 | 77.3 | 80.2 | 72.2 | 72.3 |
| Heat input, MJ/h | - | 2070 | 2050 | 2086 | 2115 | 2169 | 2325 |
| Furnace exit temp., °C | - | 987 | >802 | >832 | >835 | >794 | 873 |
| Air temperature, °C | | | | | | | |
| Pulverizer in | - | 213 | 209 | 199 | 198 | 200 | 200 |
| Pulverizer out | - | 111 | 116 | 106 | 111 | 108 | 111 |
| Secondary | - | 263 | 243 | 236 | 240 | 236 | 246 |
| Steam rate, kg/MJ | - | 0.196 | 0.205 | 0.206 | 0.217 | 0.199 | 0.195 |
| Flue gas rate, $Nm^3/MJ$ | - | 0.310 | 0.309 | 0.308 | 0.302 | 0.308 | 0.303 |
| Flue gas analyses, Volume | | | | | | | |
| $CO_2$ % | - | 14.6 | 14.7 | 14.6 | 14.5 | 14.5 | 14.5 |
| $O_2$ % | - | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.1 |
| CO ppm | - | 922 | 941 | 972 | 1011 | 955 | 964 |
| $SO_2$ ppm | - | 3483 | 1967 | 1773 | 2010 | 1651 | 1076 |
| $SO_3$ ppm | - | 2.2 | 2.6 | 2.8 | 4.2 | 2.7 | 1.7 |
| Emission rates, g/MJ | | | | | | | |
| NO | - | 0.383 | 0.390 | 0.400 | 0.409 | 0.393 | 0.392 |
| $SO_2$ | - | 3.088 | 1.740 | 1.560 | 1.735 | 1.453 | 0.934 |

Table 8 - Boiler operating conditions (fine grind)

| Components | C-1B | C-2B | C-3B | C-4B | C-5B | C-6B | C-7B |
|---|---|---|---|---|---|---|---|
| Furnace configuration | I | I | I | I | I | I | I |
| Fuel rate, kg/h | 78.8 | 86.3 | 71.0 | 69.5 | 67.0 | 67.7 | 6.51 |
| Fuel moisture, wt % | 0.00 | 0.79 | 1.20 | 1.2 | 0.00 | 0.00 | 0.00 |
| Coal fineness, wt % (Cdn std) | | | | | | | |
| +100 mesh | - | 0.7 | 0.3 | 0.5 | 0.4 | 0.1 | 0.4 |
| -100 + 140 mesh | 2.2 | 1.0 | 5.5 | 1.5 | 2.4 | 2.7 | 1.5 |
| -140 + 200 mesh | 7.9 | 1.7 | 12.1 | 7.6 | 6.6 | 15.0 | 12.3 |
| -200 + 325 mesh | 50.7 | 60.6 | 51.1 | 53.3 | 69.5 | 65.9 | 75.0 |
| -325 + 400 mesh | 21.5 | 20.9 | 18.3 | 20.8 | 10.0 | 6.3 | 3.9 |
| -400 mesh | 11.5 | 15.1 | 12.7 | 16.2 | 11.0 | 10.0 | 6.9 |
| -200 mesh | 90.0 | 96.6 | 82.1 | 90.3 | 90.5 | 82.2 | 85.8 |
| Heat input, MJ/h | 2139 | 2073 | 2074 | 2125 | 2112 | 2172 | 2178 |
| Furnace exit temp., °C | 925 | 933 | >838 | >836 | 898 | >736 | 937 |
| Air temperature, °C | | | | | | | |
| Pulverizer in | 216 | 217 | 206 | 206 | 209 | 203 | 205 |
| Pulverizer out | 121 | 111 | 112 | 114 | 123 | 110 | 118 |
| Secondary | 265 | 271 | 242 | 250 | 255 | 242 | 253 |
| Steam rate, kg/MJ | 0.192 | 0.184 | 0.208 | 0.208 | 0.207 | 0.199 | 0.201 |
| Flue gas rate, $Nm^3/MJ$ | 0.308 | 0.312 | 0.309 | 0.308 | 0.302 | 0.308 | 0.300 |
| Flue gas analyses, Volume | | | | | | | |
| $CO_2$ % | 15.6 | 14.5 | 14.7 | 14.6 | 14.6 | 14.5 | 14.9 |
| $O_2$ % | 4.0 | 4.1 | 4.0 | 4.0 | 4.0 | 4.0 | 3.9 |
| CO ppm | 45 | 45 | 62 | 66 | 100 | 42 | 48 |
| NO ppm | 822 | 1000 | 957 | 998 | 942 | 1031 | 1014 |
| $SO_2$ ppm | 259 | 3334 | 2224 | 1886 | 2195 | 1551 | 1057 |
| $SO_3$ ppm | - | 1.9 | 2.6 | 2.4 | 2.4 | 1.5 | 1.7 |
| Emission rates, g/MJ | | | | | | | |
| NO | 0.339 | 0.418 | 0.396 | 0.411 | 0.381 | 0.425 | 0.407 |
| $SO_2$ | 0.228 | 2.973 | 1.967 | 1.659 | 1.895 | 1.365 | 0.906 |

Table 9 - Fly ash characteristics (coarse grind)

| Components | C-1A | C-2A | C-3A | C-4A | C-5A | C-6A | C-7A |
|---|---|---|---|---|---|---|---|
| Precipitator inlet loading, | | | | | | | |
| $g/Nm^3$ ..... | - | 6.94 | 1.95 | 2.03 | 1.50 | 1.24 | 1.29 |
| g/MJ ..... | - | 2.15 | 0.60 | 0.62 | 0.45 | 0.38 | 0.39 |
| Combustible content, wt % ..... | - | 5.59 | 20.6 | 13.9 | 16.0 | 16.1 | 24.4 |
| Aerodynamic particle size, wt % | | | | | | | |
| +30 µm ..... | - | - | 3 | 9 | 1 | 4 | 11 |
| +10 µm ..... | - | 45 | 53 | 56 | 45 | 48 | 42 |
| +1 µm ..... | - | 97 | 96 | 96 | 95 | 95 | 94 |
| Electrical resistivity log ohm-cm | | | | | | | |
| @ 165°C ..... | - | 5.11 | 4.75 | 4.73 | - | 4.78 | 4.83 |
| @ 330°C ..... | - | 5.38 | 5.20 | 5.18 | 5.46 | 5.27 | 5.43 |
| Combustion efficiency, %* ..... | - | 97.98 | 96.77 | 98.66 | 98.58 | 98.95 | 99.22 |

*Combustion efficiency, % = $100 - \frac{33.727\ AC}{(100-C)\ Q}$

where : A = % ash in coal feed (dry basis)

C = % carbon in fly ash

Q = Calorific value of coal feed, MJ/kg (dry basis)

Table 10 - Fly ash characteristics (fine grind)

| Components | C-1B | C-2B | C-3B | C-4B | C-5B | C-6B | C-7B |
|---|---|---|---|---|---|---|---|
| Precipitator inlet loading, | | | | | | | |
| g/Nm$^3$ ..... | 2.23 | 8.24 | 2.69 | 2.07 | 1.57 | 1.21 | 0.81 |
| g/MJ ..... | 0.69 | 2.57 | 0.83 | 0.64 | 0.47 | 0.37 | 0.24 |
| Combustible content, wt % ... | 2.85 | 2.44 | 20.18 | 13.52 | 19.76 | 8.54 | 13.88 |
| Aerodynamic particle size, wt % | | | | | | | |
| +30 µm ..... | - | 6 | 3 | 5 | 1 | 7 | 5 |
| +10 µm ..... | 58 | 44 | 51 | 54 | 43 | 37 | 41 |
| +1 µm ..... | 98 | 98 | 96 | 97 | 95 | 94 | 93 |
| Electrical resistivity log ohm-cm | | | | | | | |
| @ 165°C ..... | 10.93 | - | 4.76 | 4.74 | 5.11 | 4.83 | 5.15 |
| @ 330°C ..... | - | 7.76 | 5.15 | 5.26 | 5.34 | 5.18 | 5.48 |
| Combustion efficiency, %* ... | 99.86 | 99.15 | 96.86 | 98.70 | 98.16 | 99.49 | 99.61 |

*Combustion efficiency, % = $100 - \frac{33.727\ AC}{(100-C)\ Q}$

where : A = % ash in coal feed (dry basis)

C = % carbon in fly ash

Q = Calorific value of coal feed, MJ/kg (dry basis)

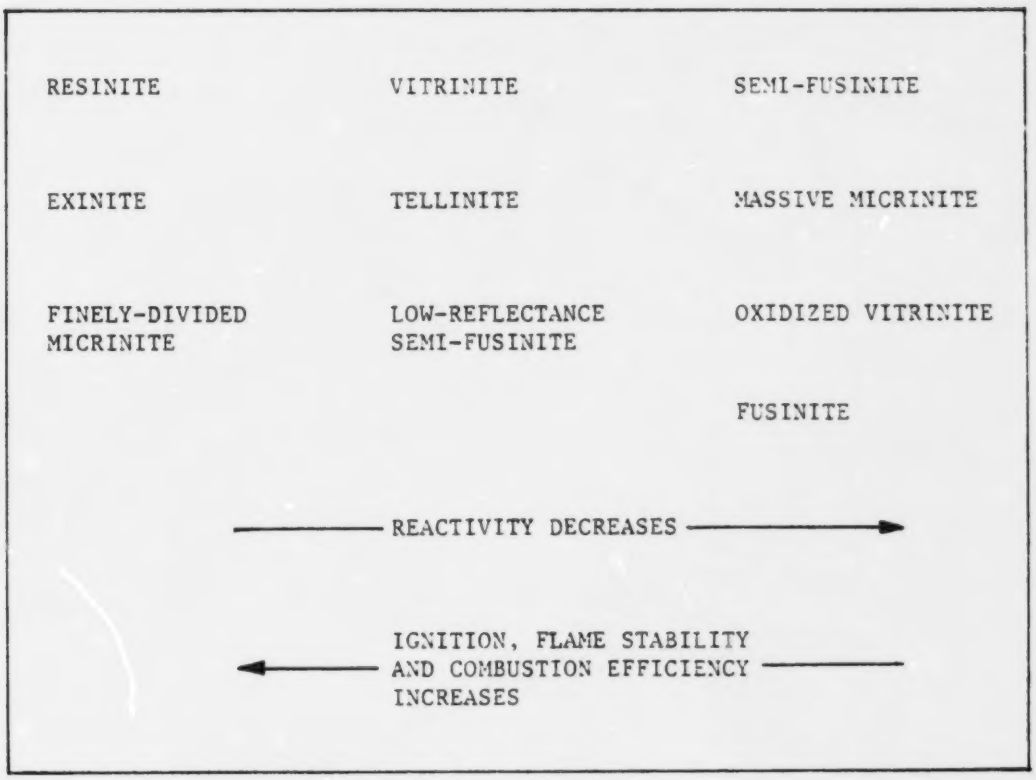


Fig. 1- Influence of coal maceral type on combustion

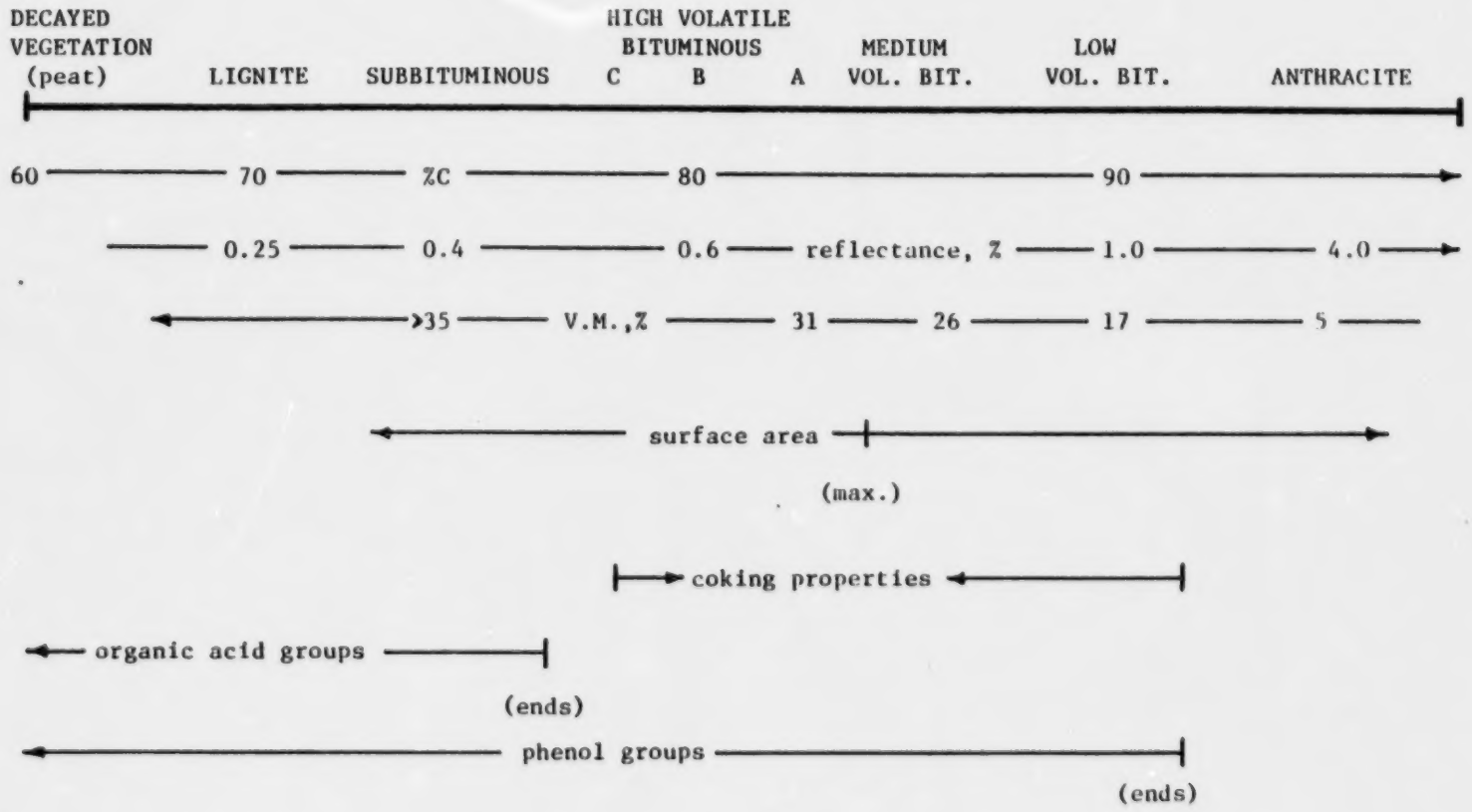


Fig. 2 - Some changes in coal composition and coal properties as a function of rank

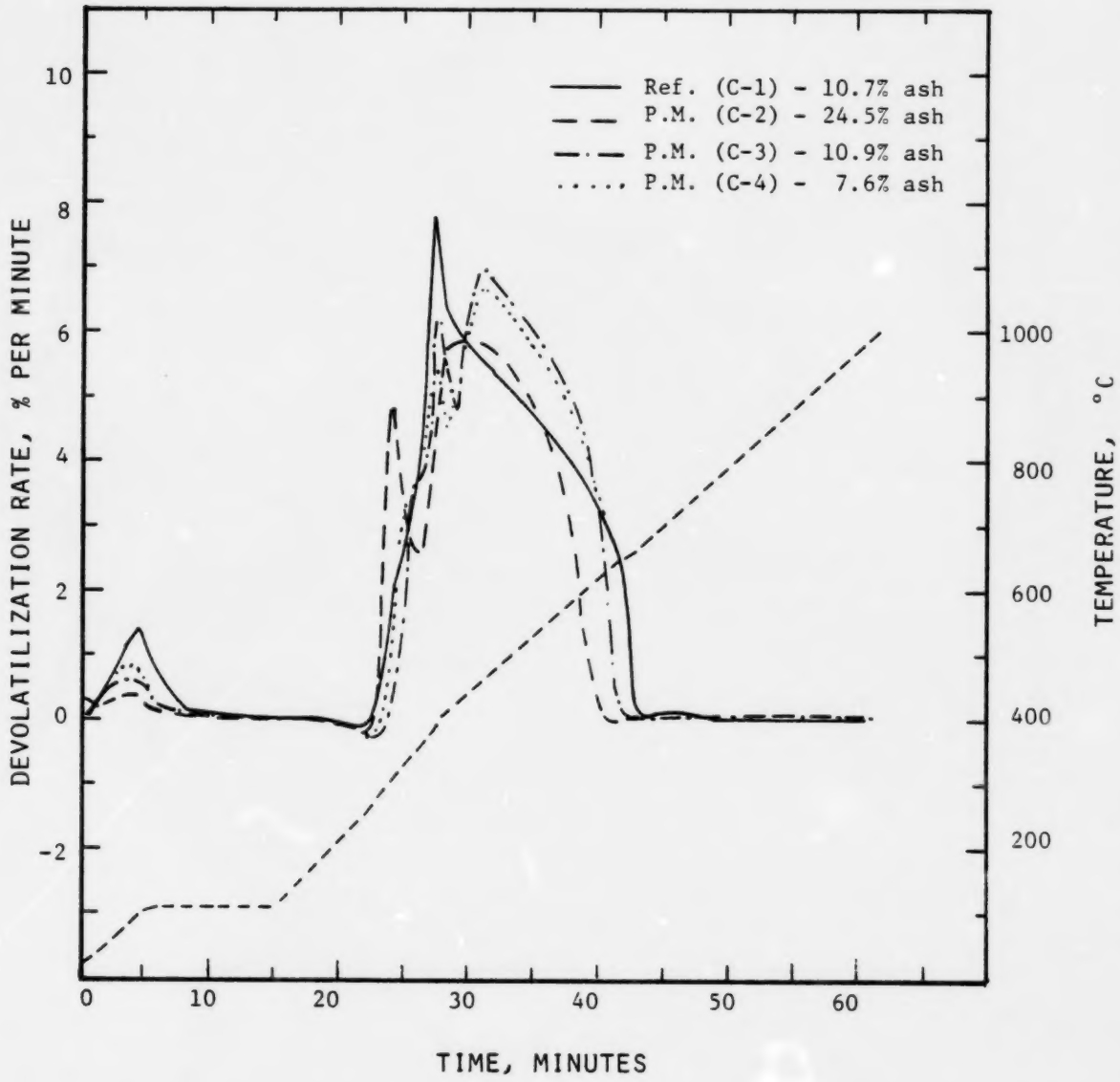


Fig. 3a - Comparative thermogravimetric analysis of Prince Mine coals and a thermal reference coal

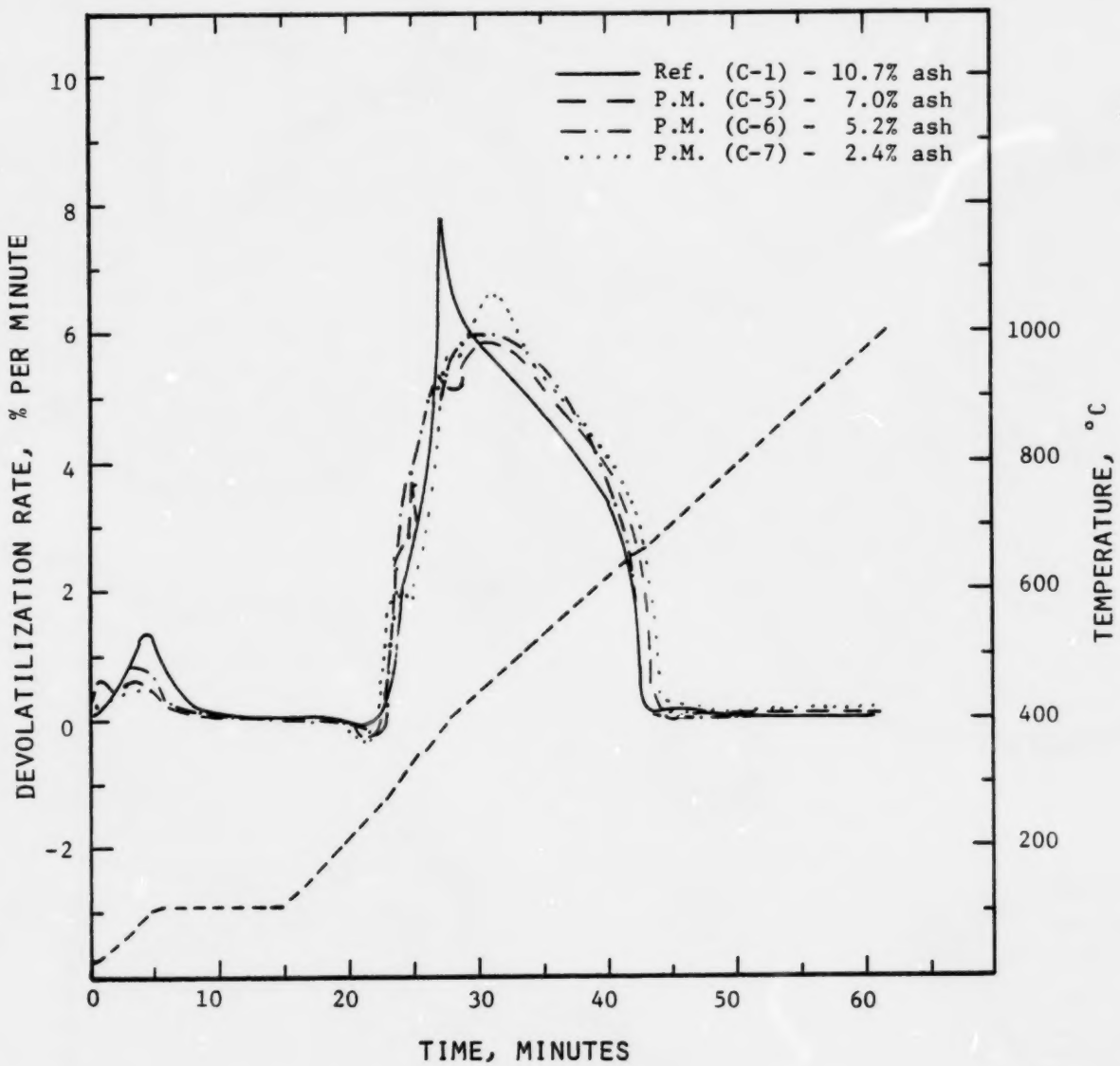


Fig. 3b - Comparative thermogravimetric analysis of Prince Mine coals and a thermal reference coal

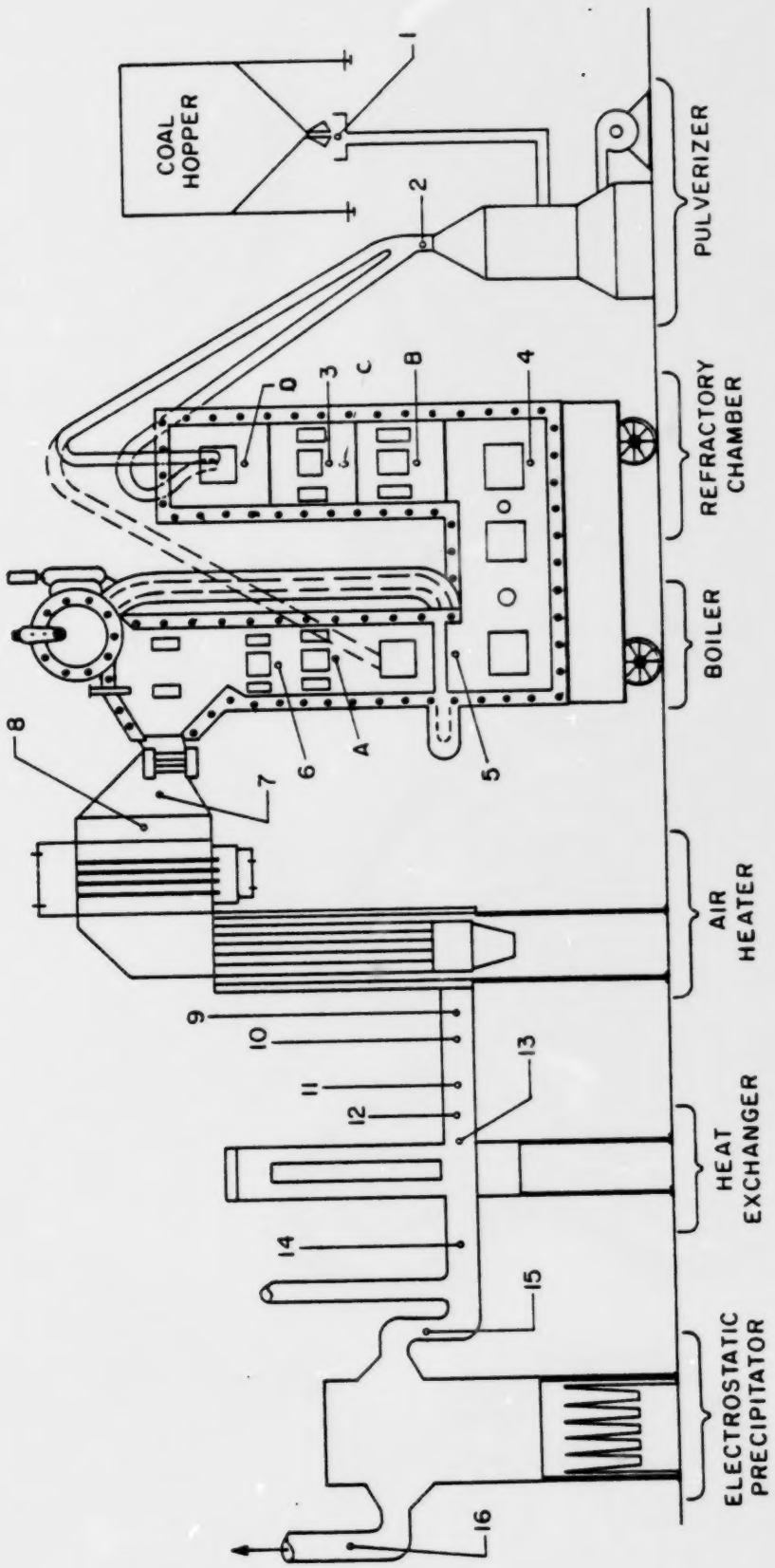


Fig. 4 - Schematic illustration of the pilot-scale boiler - showing sampling stations

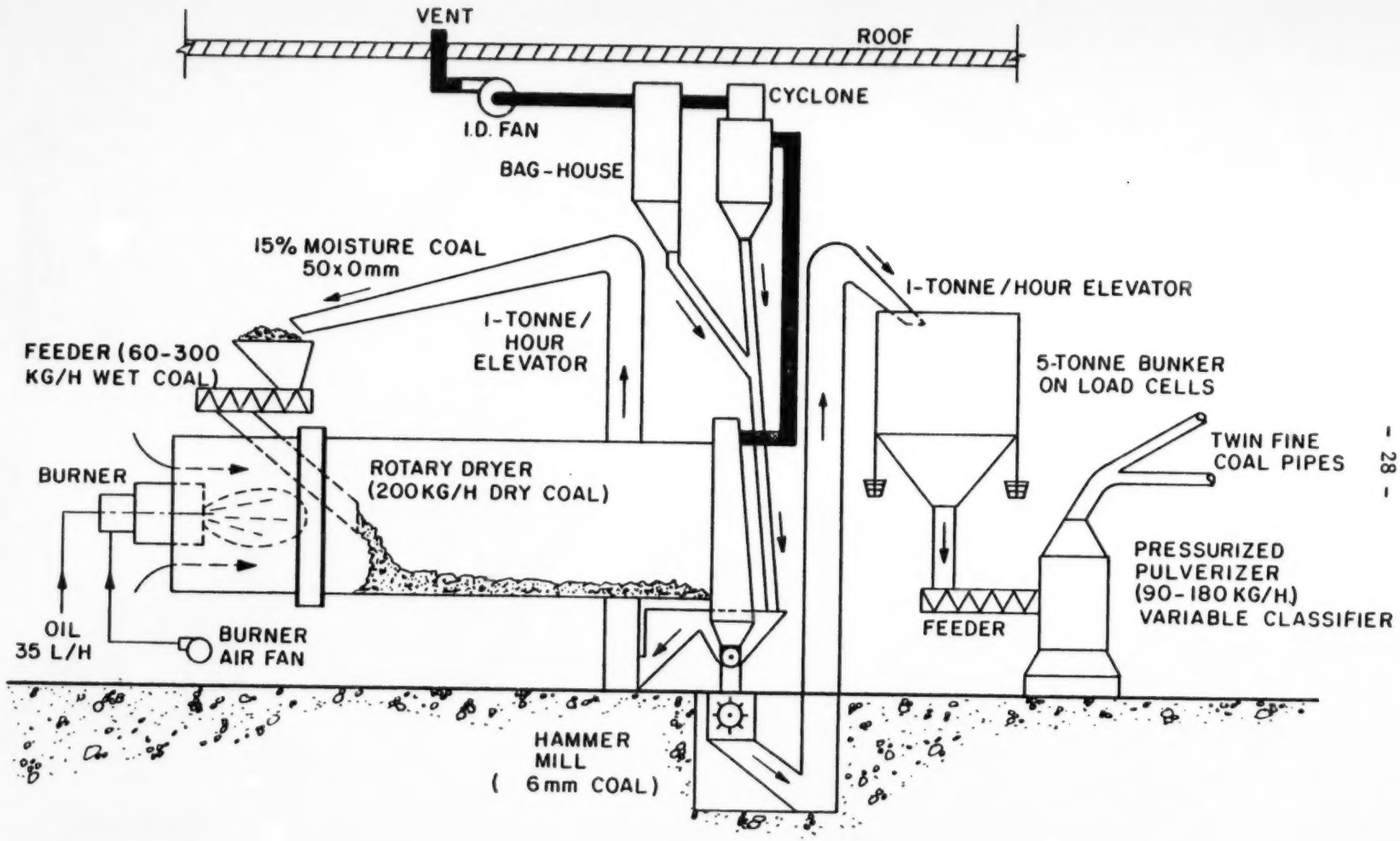


Fig. 5 - Schematic illustration of solid fuel drying and grinding system

# APPENDIX "A"

## COMBUSTION CHARTS

## FOR

## PRINCE MINE

## RAW COAL

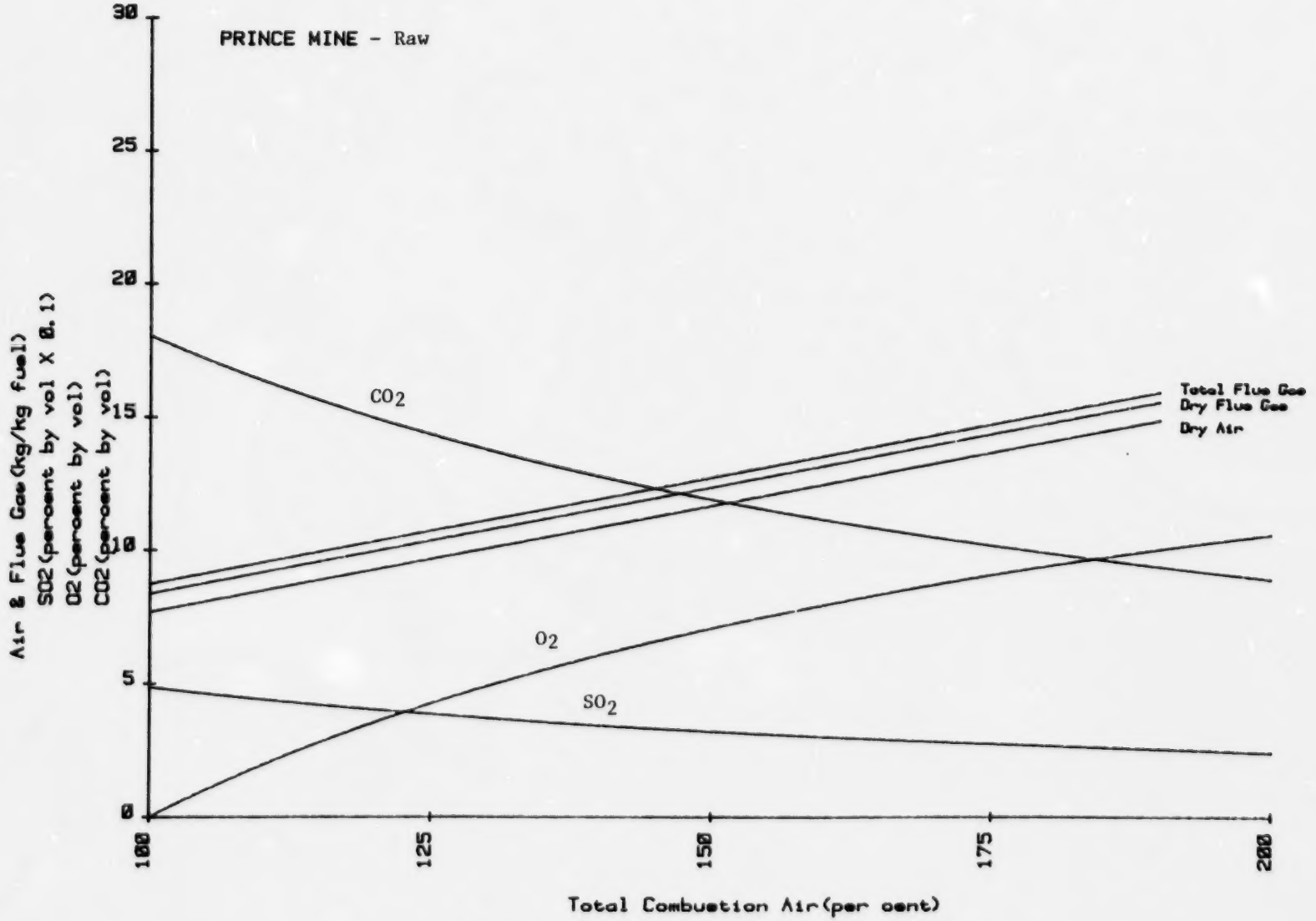


Fig. 1A - Combustion data, weight basis

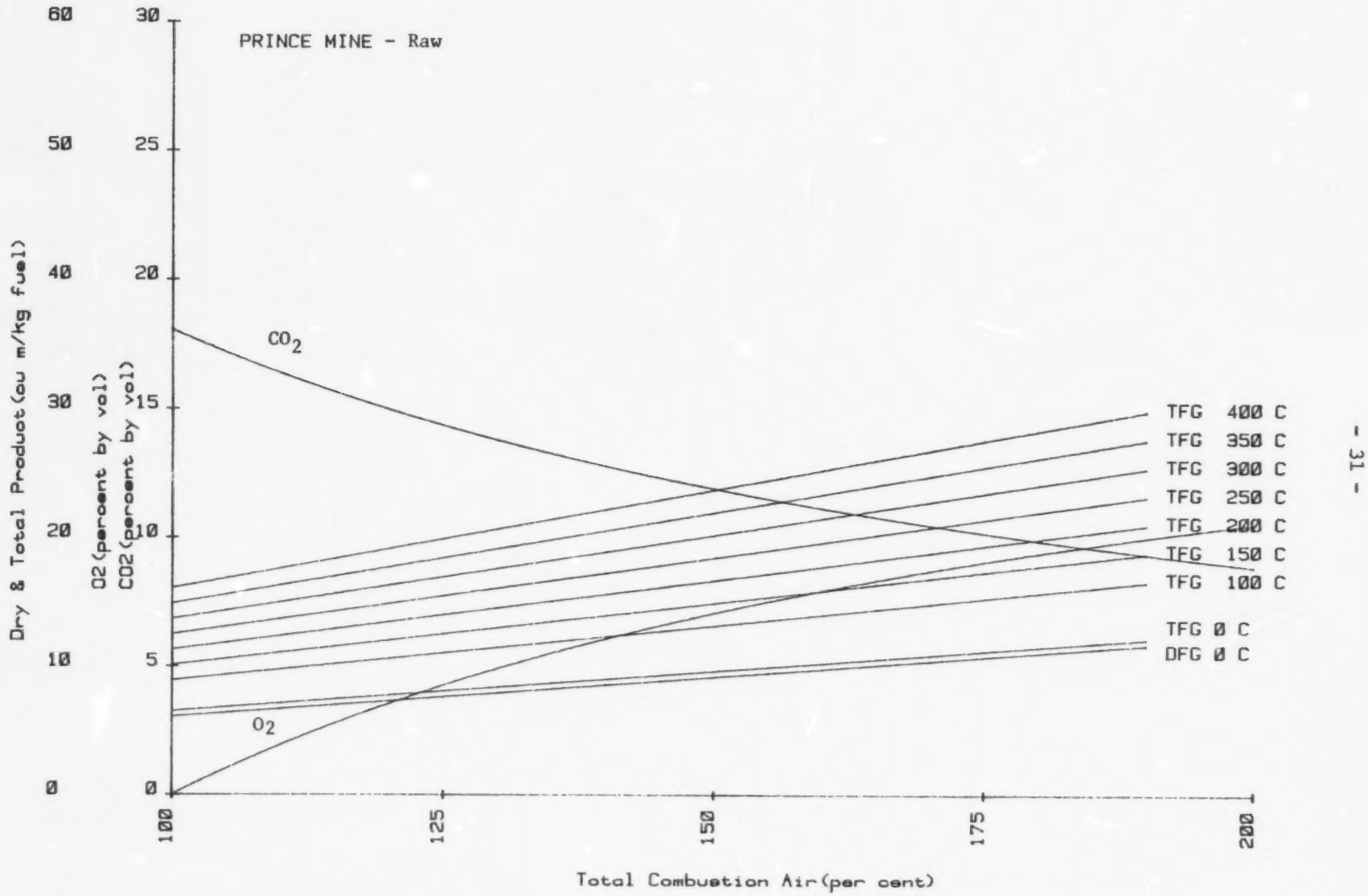


Fig. 2A - Combustion data, volume basis

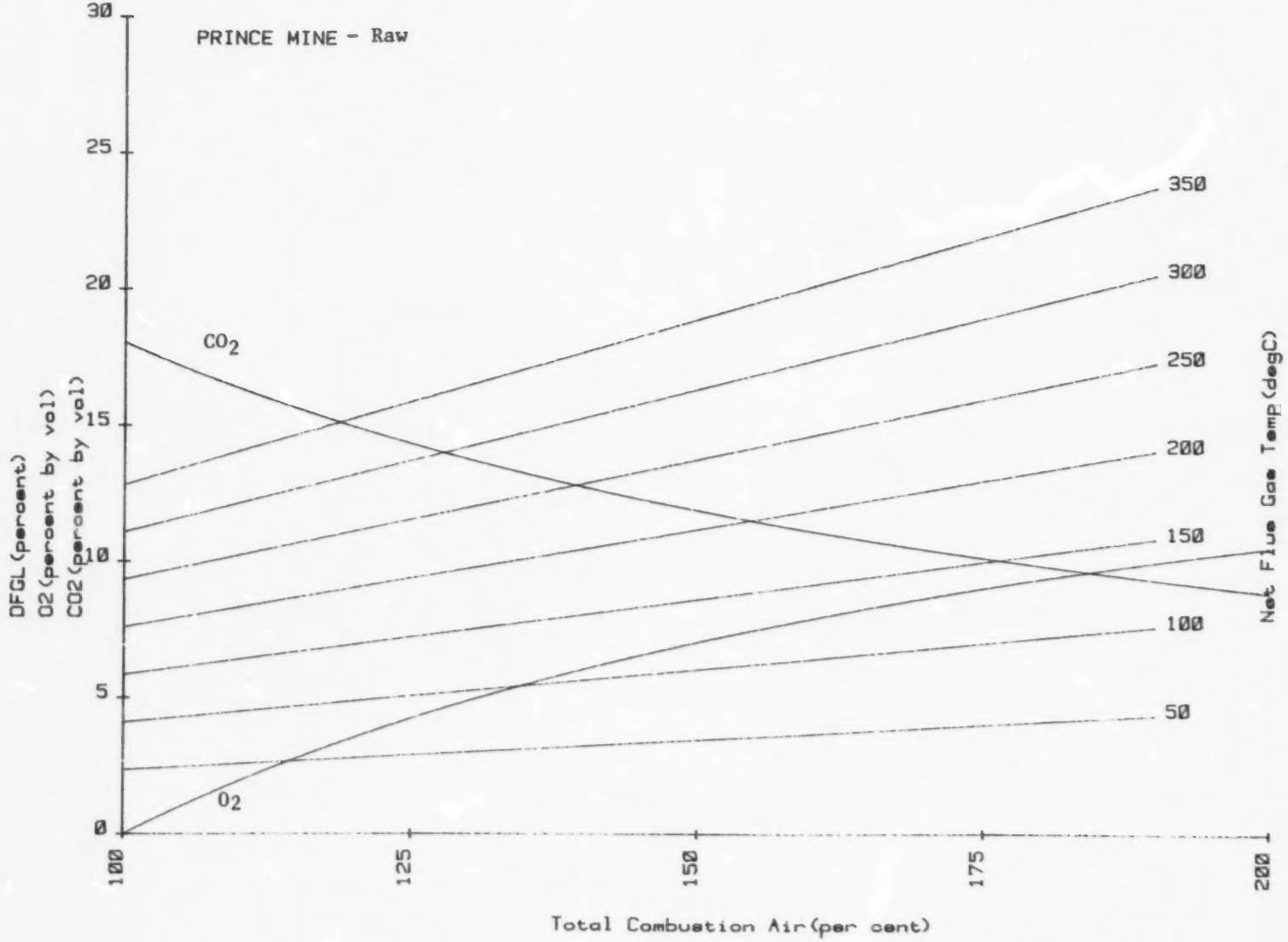


Fig. 3A - Dry flue gas loss for a range of temperature differentials

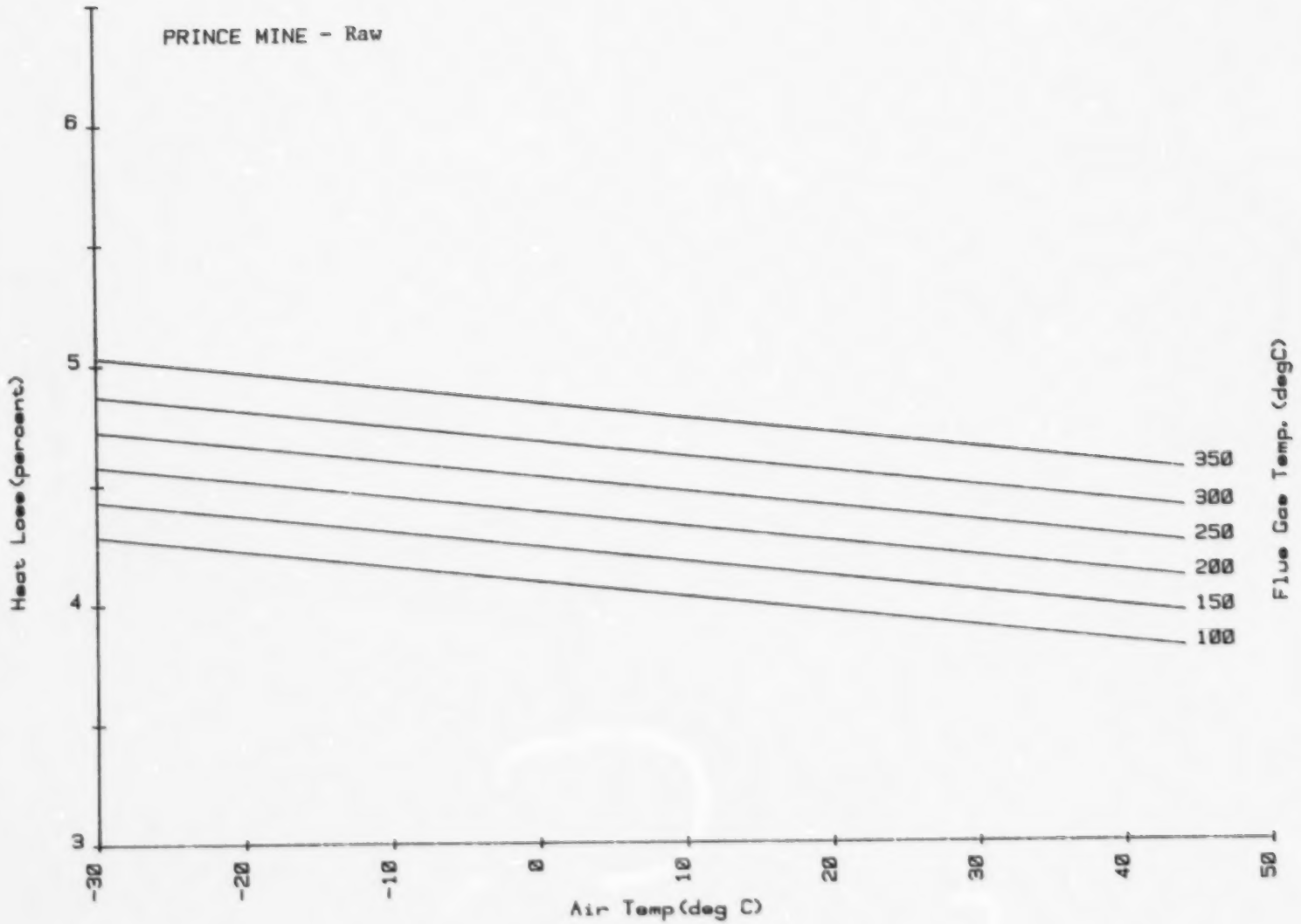


Fig. 4A - Hydrogen loss for a range of stack temperatures

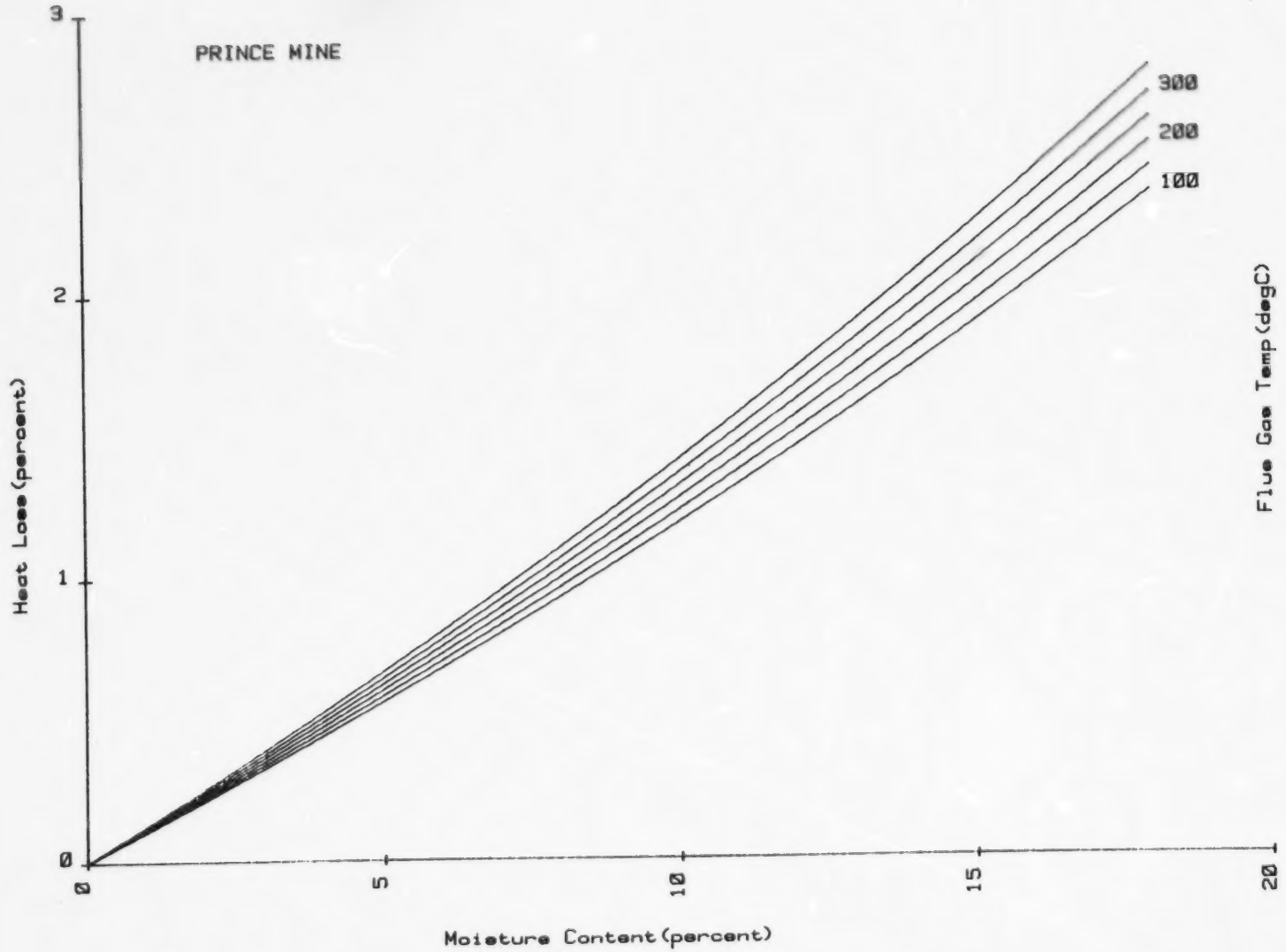


Fig. 5A - Heat loss due to moisture in coal

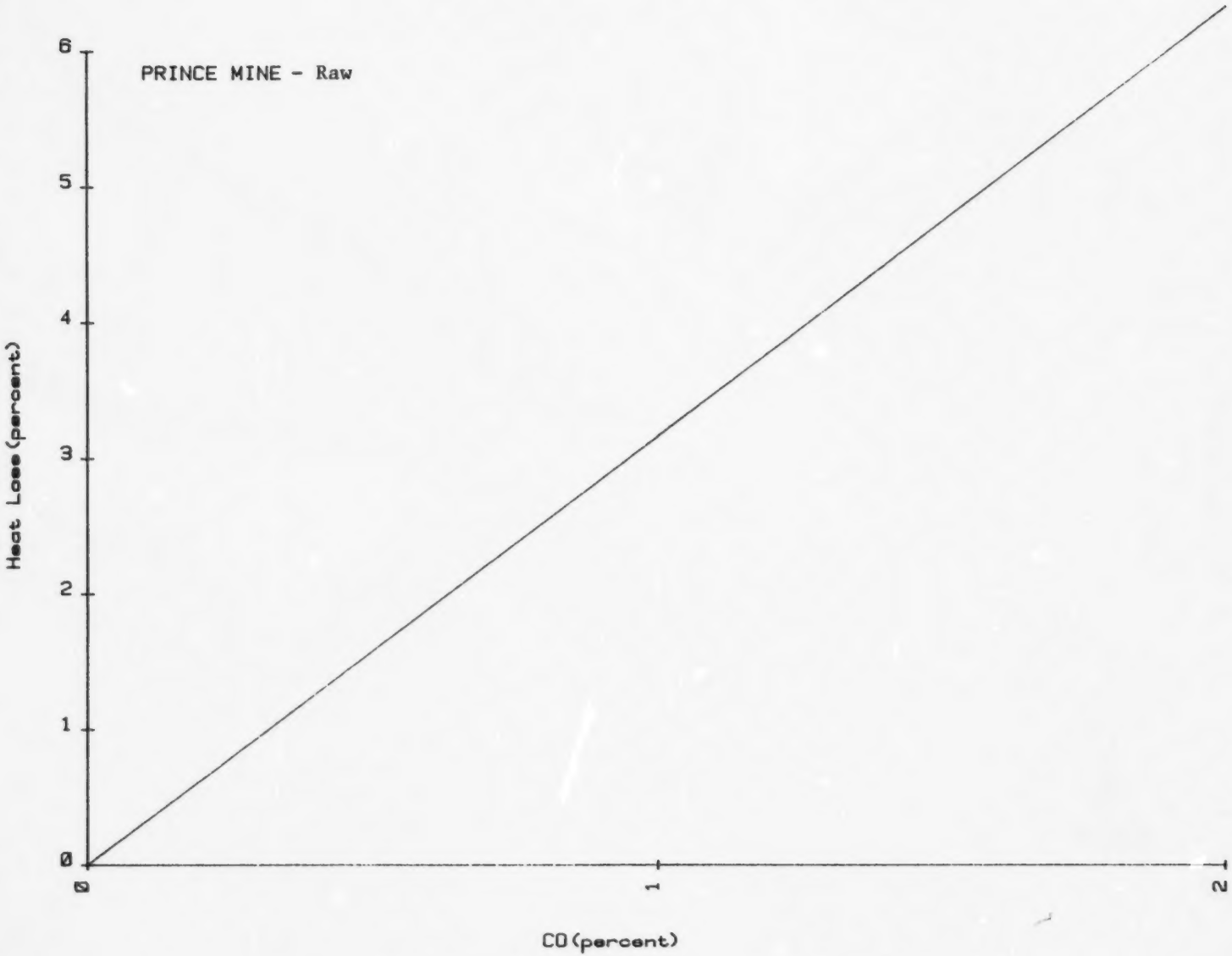


Fig. 6A - Heat loss for a range of CO concentrations (assuming negligible excess air)